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RESPONSE OF DIRECT SEEDED *PINUS PALUSTRIS* AND HERBACEOUS VEGETATION TO FERTILIZATION, BURNING, AND PINE STRAW HARVESTING

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Abstract-Fallen pine straw (needles) is a renewable biological resource valued as a mulch in horticulture and for landscaping. However, its harvesting may have detrimental long-term effects on forest soils and vegetation. To compare current pine straw harvesting practices, a randomized complete block split-plot study was established during 1990 in a 34-year-old stand of direct-seeded longleaf pine (*Pinus palustris* Mill.) that had been prescribed burned every 3 years since establishment. Practices included no fertilizer or applications of 50 kg ha^{-1} N and 56 kg ha^{-1} P in both 1991 and 1997 as the main plot treatment. The subplot management practices were prescribed burning and the mechanical baling and removal of straw. Pine straw harvesting eventually removed the forest floor and increased soil bulk density by 1993. The growth of longleaf pine was not significantly affected by treatments over a 5-year period from early 1991 to early 1996. Herbaceous plant productivity was determined in July 1997, and there were shifts in plant dominance associated with treatments. Fertilization increased current-year herbaceous plant biomass by 59% on an oven-dried weight basis. Among management practices, prescribed burning in early 1991, 1994, and 1997, with two annual straw harvests in early 1992 and 1993, resulted in the greatest herbaceous plant yields by July 1997. The lowest yields in 1997 were on plots that were either annually harvested six times or had been left untreated for over 6 years. Burning every 3 years favored pinehill bluestem (*Schizachyrium scoparium* var. *divergens* (Hack.) Gould), which is often the dominant grass on longleaf uplands in the West Gulf Coastal Plain of the U.S.A. Raking straw shifts herbaceous plant dominance to other grasses, principally the panicums (*Dicanthelium* spp. and *Panicum* spp.). The cessation of management favored bracken fern (*Pteridium aquilinum* var. *pseudocaudatum* (Clute) Heller). Published by Elsevier Science Ltd.

Keywords-Agroforestry; longleaf pine growth and yield; *Pinus palustris* Mill.; mulch; herbaceous plant productivity.

1. INTRODUCTION

Farmers world-wide use mulches to control weeds and manage soil moisture in field and horticultural crops.[1–5] Fallen conifer needles (straw) are a renewable biological resource that has traditionally been harvested for mulch.[6–9] Under good market and stand conditions in the southern United States, pine straw is worth from $24 to $324 (USA dollars) ha^{-1} yearly to the landowner and an additional $172 to $437 ha^{-1} in profits to the straw harvester.“.” Adding straw to timber and forage as products of management can increase profits substantially, and the income from straw may exceed that from timber.‘*

Despite the immediate economic opportunities, repeated removal of the forest floor may adversely affect pine tree growth and yield and change herbaceous plant community relationships.[7,13] Fertilization is recommended where pine straw is being harvested.” The objectives of this study were to determine how pine straw harvesting practices, which included prescribed burning and the mechanical baling and removal of straw, influence longleaf pine (*Pinus palustris* Mill.) productivity, straw yields, needle fall patterns, soil bulk density,

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plant and soil nutrition, and herbaceous plant productivity and species dominance.

2. MATERIALS AND METHODS

2.1. *Study site*

The 40 ha study site is a gently rolling area in Rapides Parish, LA, with Ruston and Smithdale fine sandy loam soils (Typic Paleudults, fine-loamy, siliceous, thermic). The site supports longleaf pine stands that originated from direct seeding in 1956 and was 34 years old from seed in 1990. The site was continually prescribed burned about every 3 years as part of a range of management program, which retarded development of woody vegetation in the understorey. The whole stand was last burned in 1987.

2.2. *Treatment establishment*

Four 1.3 ha research blocks were installed in the spring and early summer of 1990. Blocking was based on topography, forest cover conditions, and the basal area of the longleaf pine trees. In August 1990, the understorey vegetation was rotary mowed to create uniform understorey conditions and to facilitate plot establishment.

To examine several of the management practices associated with straw harvesting, we installed a randomized complete block split-plot study with the four blocks as replicates. In total, there are 32 0.16 ha subplots (four blocks by two main plots by four subplots). The two main-plot treatments within each block were: (1) no fertilizer applied and (2) 50 kg ha^{-1} N and 56 kg ha^{-1} P broadcast evenly over the entire main plot in both April 1991 and May 1997 as 280 kg ha^{-1} diammonium phosphate (DAP) fertilizer.

Management of the subplots for pine straw included: (1) Control-No burning or mowing after 1990; (2) Burned only-The subplots were triennially burned in March 1991, February 1994, and March 1997; (3) Burned and two straw harvests-In addition to treatment 2, the subplots were rotary mowed in July 1991 and 1992, and the straw was harvested in early 1992 and 1993; and (4) Annually harvested-The subplots were rotary mowed in July 1991 and burned in August 1991 to prepare them for straw harvesting, the plots were again rotary mowed each July from 1992 to 1996, and the straw was annually harvested in early 1992 to early 1997.

2.3. *Burns*

Burning was with strip-head fires set with drip torches, which were monitored to determine their intensity. Just before firing in 1991 and 1994 and within the interior sampling plot, a combustible fuel sample was collected on five randomly located fuel-monitoring plots that measured 0.3 x 0.3 m each.[14] Fuel samples were again collected one week after the burns. These samples were used to determine available fuel moisture on a dry weight basis.

Byram's fire intensity ($I = Hwr$), the quantitative expression of fire behavior, was calculated for the 1991 and 1994 burns:” I is the fire intensity in kJ s^{-1} m^{-1}, r is the rate of spread in m s^{-1}, w is the fuel consumed in kg m^{-2}, and H is the low heat of combustion of fuels in kJ kg^{-1}. Rate of spread (Y) was measured for each burned plot. W was the difference in oven-dry weight of combustible fuels between the fuel-load samples taken before and after each burn. H was calculated as follows: 19254 − 24 (% moisture content of combustible fuels on a dry weight basis).[15,16]

One month after the 1991 and 1994 prescribed burns, the percentage of crown scorch was estimated for each pine tree on the burned subplots. Unburned subplots were also examined to determine how much natural discoloration of foliage could have been mistaken for scorch, but little false-scorch was found. Fire intensity was not measured for the March 1997 burns, but crown scorch was observed to be minimal following this 1997 burn.

2.4. *Straw harvesting practices*

Treatments 3 and 4 were rotary mowed in July to prepare them for straw harvesting. The straw was harvested by standard commercial methods. The straw was first collected in windrows with a tractor mounted straight-bar rake. Large limbs and cones were removed, and the straw was mechanically baled. The bales were weighed and a subsample taken to determine moisture content and dry matter production for the early 1992 to 1995 harvests.

2.5. *Foliage, litter and soil sampling*

On each subplot, five 0.91 m^2 litter traps were systematically located within the 0.09 ha measurement area for the monthly collection of needle fall samples. For nutrient analyses, 10 soil samples were randomly collected in April 1991 and 1993 to a depth of 15 cm. Living needle samples were collected from the upper crowns of five dominant longleaf pines in February 1995 before the designated subplots were burned. Five bulk density samples of the mineral soil were randomly taken in July 1994 and May 1997 to a depth of 10 cm.

Harvested straw, litter, and living needle samples were oven dried at 70°C to a constant weight. After the samples were weighed, they were ground in a Wiley Mill. Following sulfuric acid/cupric sulfate digestion, the nitrogen, phosphorus, and potassium content of the living needles were determined by ammonium probe, colorimetry, and atomic absorption spectrophotometry, respectively. For the soil samples, the phosphorus content was determined by the Bray P2 method, and the potassium content by extraction with 1 N ammonium acetate.

2.6. *Tree growth*

An interior 0.09 ha area within each subplot was used for measurement and sampling purposes. In January 1991 and 1994 and February 1996, dbh (diameter of stem 1.4 m above the ground) and tree height of longleaf pines over 10 cm dbh were measured, and the inside-bark volume per tree was calculated using the relationships of Baldwin and Saucier."

2.7. *Herbaceous plant sampling*

In July 1997, herbaceous plants were inventoried and current-year above ground biomass samples were collected on three randomly located 0.022 m^{-2} quadrats per subplot. The biomass samples were divided into seven taxa—pinehill bluestem (*Schizachyrium scoparium* var. *divergens* (Hack.) Gould), slender bluestem (S. *tenerum Nees)*, other bluestems (*Andropogon* spp.), other grasses (principally the low panicums (*Dicanthelium* spp.) and tall panicums (*Panicum* spp.)), grasslike plants, forbs, and ferns.

The subdivisions were made based on prior knowledge of which taxa are most important on upland longleaf pine landscapes and the vegetation indigenous to central Louisiana.[18] For each subplot, the subdivided biomass samples were individually oven dried at 80°C to a constant weight and then weighed.

2.8. *Power analysis*

The composition of direct-seeded longleaf pine stands is normally very variable. We were able to reduce the degree of inherent variability within research blocks by careful plot selection to limit the range in longleaf pine basal area among subplots. However, the problem of type II error, the false acceptance of the null hypothesis, is a major concern in ecological studies because natural variation is always an issue regardless of the care taken to reduce it.[19,20] During the establishment of this study, several blocks of plots were discarded because of the high degree of variability in longleaf pine basal area at their locations. Although the study area is large (40 ha) in comparison with the actual area in research plots, few locations remained that could have provided additional blocks of plots that would have lessened the problem of controlling type II error.

We did a power analysis based on the pretreatment data collected in January 1991 and the post-treatment data collected in February

Table 1. Analysis of the probability of failing to reject the null hypothesis when in fact the null hypothesis is false (power of the test)

Measurement variables	Power of the test at selected alpha levels		
	α = 0.05	α = 0.10	a = 0.15
January 199 1			
Dbh (cm)	0.207	0.320	0.406
Total height (m)	0.116	0.119	0.271
Basal area per hectare (m^2 ha-‘)	0.139	0.231	0.307
Inside-bark volume per hectare ($m^3 ha^{-1}$)	0.125	0.212	0.285
February 1996			
Dbh (cm)	0.244	0.368	0.460
Total height (m)	0.443	0.587	0.677
Basal area per hectare (m^2 ha-‘)	0.284	0.415	0.509
Inside-bark volume per hectare (m^3 ha-‘)	0.119	0.204	0.278

Based on the initial longleaf pine measurements taken in January 1991 before treatments were initiated and on the periodic increment for the next five growing seasons

1996[20] (Table 1). Even at a high alpha level of 0.15, the power of this experiment did not exceed 0.41 for the pretreatment data. A power of 0.80 or better is desirable.

For the February 1996 results, the power of the test for an alpha level of 0.15 approached 0.68 (Table 1). However, this *posteriori* power analysis may be useful only in interpreting results that have already failed to reject the null hypothesis.'" In one respect, it only confirms what one had learned already, and is simply a way of re-stating the statistical significance of the tests.[20]

2.9. *Data analysis*

Given the low power associated with this experiment, and based on the pretreatment basal area findings, we selected an alpha level of 0.15. A higher-than-normal alpha level is also desirable because of the natural slowing of height and diameter growth rate as pine stands grow older, and because of the inherent variability in tree spatial distribution and stem size common in direct-seeded longleaf pine stands. The actual probabilities are reported in the tables or are given in the text for the use of the reader.

Differences among treatments in the initial measurements for longleaf pine, longleaf pine needle fall, nutrition of living foliage, growth over five growing seasons, soil bulk density, and total herbaceous plant biomass were subjected to analysis of variance for a randomized complete block split-plot design using SAS statistical software.[21] Using essentially the same model, the final longleaf pine growth and yield and soil nutrition data were examined by analysis of covariance, with the appropriate variable from the original data set as the covariate.

The non-orthogonal linear contrasts used to compare subplot treatment differences were: (1) control vs. stand management (burned only + burned and two harvests + annually harvested); (2) burned only vs. burned and two harvests; and (3) burned and two harvests vs. annually harvested. The amounts of forest floor material removed from harvested treatments were compared by chi-square tests of independence using SAS statistical software.[21]

3. RESULTS AND DISCUSSION

A primary concern with pine straw harvesting among forest managers in the U.S. Department of Agriculture, Forest Service, is, "How detrimental to forest vegetation would be one or two straw harvests over a lo-year period of time?" To address this concern, we stopped harvesting straw on subplot treatment 3 once it was apparent after the January 1994 measurement that there were no statistical differences between treatments 3 and 4 (Table 2). The standard management practice of triennial burning continued after the cessation of straw harvesting on treatment 3 just as it would have normally continued on Forest Service lands.

We did this because, based on past experience with prescribed burning, differences in how vegetation responds between two noncatastrophic fires are minimal-that is the March 1991 burn in treatment 3 vs. the August 1991 burn in treatment 4-in a longleaf pine landscape that has been subjected to fire over several decades." A single difference in the season of burning is not as important as total fire history. In this research study, we felt it was more important to determine to what extent pine sites might recover from the adverse effects, if any, of forest floor removal.

3.1. *Burning effects*

For the March 1991 burn, fireline intensity averaged 218 $kJ\,s^{-1}\,m^{-1}$ on subplot treatments 2 and 3, which was above the expected range of O-173 $kJ\,s^{-1}\,m^{-1}$.[22] The March burn scorched 15% of the longleaf pine foliage. Fireline intensity averaged 163 $kJ\,s^{-1}\,m^{-1}$ for the August 1991 burn on subplot treatment 4, and the August burn scorched only 2% of the foliage. After two straw harvests, the February 1994 burn had an intensity of 150 $kJ\,s^{-1}\,m^{-1}$ on subplot treatment 3, but fireline intensity was 237 $kJ\,s^{-1}\,m^{-1}$ on subplot treatment 2. As a result, there was no crown scorch after two harvests but 11% crown scorch on the burned-only subplots. The low fire intensity and lack of scorch after two harvests undoubtedly resulted from the continual removal of the fuel bed. The March 1997 burn caused little crown scorch on either treatment 2 or 3.

3.2. *Needle full patterns*

Falling longleaf pine needles were collected monthly.[23] From 1991 to 1994, 17% of the needles fell from January to July (663 kg ha^{-1}) and the total annual needle fall averaged 3944 kg ha^{-1} (Table 3). The low amount of needle

Table 2. Number of surviving longleaf pines and the least-squares mean values for longleaf pine dbh, total height, basal area, and inside-bark (i.b.) volume per hectare prior to (January 1991) and after 3 years (January 1994) and 5 years (February 1996) of treatment

Main and subplot treatments	Number of pine trees ha^{-1}	January 1991 Dbh cm	Total height m	Basal area $m^2 ha^{-1}$	i.b. Volume $m^3 ha^{-1}$	January 1994 Dbh cm	Total height m	Basal area $m^2 ha^{-1}$	i.b. Volume $m^3 ha^{-1}$	February 1996 Dbh cm	Total height m	Basal area $m^2 ha^{-1}$	i.b. Volume $m^3 ha^{-1}$
No fertilizer													
Control	330	21.3	21.4	19.6	168.5	29.5	22.1	22.1	192.2	30.6	22.8	23.7	221.1
Burned-only	325	27.9	21.5	20.3	174.3	29.5	22.1	21.9	191.6	30.6	22.8	23.5	220.2
Burned and two straw harvests	317	28.1	21.6	19.9	171.9	29.2	22.1	21.7	188.6	30.3	22.8	23.2	217.6
Annually harvested[a]	298	29.0	21.3	19.9	169.9	29.3	21.9	21.7	188.5	30.2	22.7	23.0	213.4
	318	28.1	21.4	19.9	171.2	29.4	22.1	21.9	190.2	30.4	22.8	23.4	218.1
50 kg ha^{-1} N and 56 kg ha^{-1} P													
Control	298	28.6	21.2	19.4	165.7	29.5	22.1	22.0	191.1	30.4	23.0	23.3	218.7
Burned-only	325	27.6	21.2	19.6	166.8	29.5	22.2	22.0	191.8	30.4	22.9	23.4	219.3
Burned and two straw harvests	322	27.6	20.9	19.9	168.0	29.4	22.0	21.9	190.9	30.5	23.0	23.4	220.9
Annually harvested[a]	325	27.5	20.4	19.6	160.0	29.6	22.1	22.2	192.8	30.6	23.0	23.6	221.8
	318	27.8	20.9	19.6	165.1	29.5	22.1	22.0	191.7	30.5	23.0	23.4	220.2
		Analysis of variance (Probability > F-value)				Analysis of covariance[b] (Probability > F-value)				Analysis of covariance[b] (Probability > F-value)			
Block	0.0066	0.0228	0.6782	0.0001	0.0069	0.7867	0.0586	0.6759	0.8207	0.3397	0.0320	0.6984	0.1765
Fertilizer	1.0000	0.5064	0.2843	0.0114	0.1286	0.2126	0.5989	0.2223	0.2817	0.7505	0.2279	0.7198	0.4511
Main plot error mean square	567.493	0.7182	1.1875	0.0181	66.6446	0.0402	0.0349	0.1216	8.0456	0.1211	0.0810	0.2984	39.864
Subplot treatments	0.8867	0.9552	0.6468	0.4244	0.5706	0.2548	0.7504	0.2442	0.3613	0.6500	0.8405	0.5961	0.8397
Control vs. stand management	0.7678	0.9934	0.6402	0.1431	0.7120	0.3427	0.6195	0.1475	0.3419	0.4209	0.5942	0.3183	0.6449
Burned-only vs. burned and two straw harvests	0.7723	0.8736	0.8412	0.8748	0.8966	0.0789	0.4965	0.1800	0.1375	0.4585	0.9463	0.6137	0.8532
Burned and two harvests vs. annually harvested	0.6647	0.7022	0.3647	0.5737	0.2731	0.3951	0.7758	0.3926	0.4966	0.8534	0.5003	0.7160	0.5760
Fertilizer by subplot interaction	0.4644	0.5503	0.8142	0.7064	0.8455	0.2301	0.4966	0.1694	0.1737	0.1941	0.8477	0.1254	0.2500
Pretreatment-covariate						0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
Subplot error mean square	1337.78	3.692	0.7603	0.3251	79.7789	0.0306	0.0336	0.0661	5.9578	0.0610	0.0594	0.1527	30.8440

[a]At the time of the January 1994 measurement, two annual straw harvests had been completed in early 1992 and 1993. At the time of the February 1996 measurement four annual straw harvests had been completed in early 1992 to early 1995.

[b]The January 1991 results were used as the covariate variables in the January 1994 and February 1996 data analyzes

Table 3. Average oven-dried weight of needle fall from 1991 to 1994 subdivided into early (January-July) and late (August-December) periods

Main and subplot treatments	January to July (kg ha^{-1})	August to December (kg ha^{-1})	Yearly total (kg ha^{-1})
No fertilizer			
Control	612	3216	3828
Burned-only	784	3264	4048
Burned and two straw harvests	684	3356	4040
Annually harvested[a]	602	3225	3827
	670	3265	3936
50 kg ha^{-1} N and 56 kg ha^{-1} P			
Control	642	3470	4112
Burned-only	806	3129	3935
Burned and two straw harvests	627	3067	3693
Annually harvested[a]	547	3521	4069
	655	3297	3952
		Analysis of variance (Probability > F-value)	
Block	0.3619	0.3965	0.3620
Fertilizer	0.8592	0.7915	0.9296
Main error mean square	38862	77183	19003
Subplot treatments	0.0580	0.7564	0.9280
Check vs. stand management	0.4546	0.6229	0.8341
Burned-only vs. burned and two straw harvests	0.0864	0.9440	0.5377
Burned and two harvests vs. Annually harvested	0.3067	0.4326	0.6878
Fertilizer by subplot interaction	0.8988	0.4051	0.3583
Subplot error mean square	18833	129978	126189

[a]The straw had been annually harvested three times in early 1992, 1993, and 1994

fall from January to July was consistent throughout the 4-year period.

The burned-only subplots had greater needle fall than the burned and two straw harvests treatment in January to July (Table 3). This was the direct result of the higher than normal needle fall that followed the 199 1 and 1994 prescribed fires on the burned-only treatment.[23] These two burns scorched an average of 13% of the longleaf pine foliage on the burned-only subplots. Despite the variability in needle fall among years,[23] there were no statistical differences among treatments, fertilization or stand management, in the average amount of needle fall from August to December or in the total yearly needle fall from 199 1 to 1994 (Table 3).

3.3. *Harvesting the forest floor and soil bulk density*

In the first year, more forest litter was harvested from the annually harvested subplots than from the burned and two harvests subplots-6388 vs. 5229 kg ha^{-1}, respectively (Table 4). There were no treatment differences in the second year of harvesting. On the annually harvested subplots, 6635 kg ha^{-1} of forest floor material was harvested in the third year and 5643 kg ha^{-1} was harvested in the fourth year. More forest litter was harvested than was added on a yearly basis as litter fall (Table 3), so older forest floor material was being removed during each harvest. We observed that the mineral soil was eventually left bare on much of the plot area until new needle casts and herbaceous vegetation had developed again covering the soil. The loss of the forest floor is commonly observed after burning and the continual mechanical harvesting of straw.

Pine straw harvesting increased the bulk density of the mineral soil by July 1994. The use of equipment and exposure of the soil to the impact of rainfall probably resulted in the greater bulk density. Bulk density averaged 1.33 g cm^{-3} on the controls, 1.34 g cm^{-3} on the burned-only subplots, 1.39 g cm^{-3} after two harvests on subplot treatment 3, and 1.44 g cm^{-3} after three harvests on subplot treatment 4. The probabilities > F-value for contrasts 1, 2, and 3 were 0.0119, 0.0547, and 0.1492, respectively.

Table 4. Oven-dried weight of forest floor harvested annually for 2 or 4 years

	Year of harvest			
Main and subplot treatments	First (kg ha^{-1})	Second (kg ha-‘)	Third (kg ha^{-1})	Fourth (kg ha-‘)
No fertilizer				
Burned and two straw harvests	5358	5122		
Annually harvested	6706	5246	6843	5901
	6032	5184	6843	5901
50 kg ha^{-1} N and 56 kg ha^{-1} P				
Burned and two straw harvests	5099	5461	–	
Annually harvested	6070	5039	6427	5385
	5584	5250	6427	5385
	Nonparametric analyses (Probability > F-value)			
Block	0.2235	0.0542	0.0079	0.0862
Fertilizer	0.5243	0.8561	0.8574	0.3836
Subplot treatment	0.840	0.6809	–	
Fertilizer by subplot interaction	0.3465	0.8568		–

“The subplots were not raked after the second year to allow the vegetation to begin recovering from treatment.
Corresponds to the number of harvests prior to the January 1994 and February 1996 longleaf pine measurements, respectively

In May 1997, bulk density averaged 1.25 g cm^{-3} on the controls, 1.28 g cm^{-3} on the burned-only subplots, 1.32 g cm^{-3} 4 years after the last straw harvest on subplot treatment 3, and 1.39 g cm^{-3} after six harvests on subplot treatment 4. In general, stand management increased soil bulk density. More specifically, there was no longer a significant difference in soil bulk density between the burned-only and burned and two harvests treatments. The actual difference in bulk density between the burned and two harvests and annually harvested treatments increased from 0.05 g cm^{-3} in 1994 to 0.07 g cm^{-3} in 1997. These shifts in bulk density probably resulted because of soil recovery following the stoppage of harvests on subplot treatment 3 whereas harvesting continued on subplot treatment 4. The probabilities > F-value for contrasts 1, 2, and 3 were 0.0086, 0.1975, and 0.0395, respectively.

3.4. *Nutrient concentrations in soil and pine foliage*

The application of fertilizer is recommended where pine straw is being harvested.” Based on work with loblolly pine[24] and preliminary work in this study, phosphorus was believed to be the limiting nutrient on this forest site. The application of DAP fertilizer added both phosphorus and nitrogen to the soil, and available soil phosphorus was over 15 times greater on the fertilized plots (15.4 mg kg^{-1}) than on the unfertilized plots (0.81 mg kg^{-1}) 2 years after treatment (probability > *F*-value = 0.0020).

As a result, fertilization also significantly increased the concentration of phosphorus in the living needles of the longleaf pines from 0.717 g kg^{-1} on unfertilized plots to 0.914 g kg^{-1} on fertilized plots (probability > *F*-value = 0.0033). However, the concentration in the foliage on the fertilized plots was still only marginally acceptable for optimal pine development.[25,26]

The foliar phosphorus concentrations among the subplot treatments averaged 0.830, 0.829, 0.776, and 0.826 g kg^{-1} P on the control, burned-only, burned and two harvests, and annually harvested treatments, respectively. The difference in concentration between the burned-only and burned and two harvests treatment and between the burned and two harvests and annually harvested treatments was significant (probabilities > F-value = 0.0814 and 0.0957, respectively), but we can not explain this pattern of response nor do we believe the differences in foliar phosphorus are biologically significant.

Soil potassium (0.05 cmol kg^{-1}) and foliar potassium (3.6 g kg^{-1}) were deficient on all treatments.[27] There were no treatment effects on soil potassium. Foliar potassium concentrations were greater on the control (3.5 g kg^{-1}) and annually harvested treatments (3.5 g kg^{-1}) than on the burned-only (3.1 g kg^{-1}) and burned and two harvests (3.1 g kg^{-1}) treatments (probability > F-value = 0.1134 for contrast 1 and 0.0479 for contrast 3). Scorched needles would not be able to translocate potassium before senescence. So, the trees may be developing a potassium deficiency associated with a greater loss of potassium from the trees as the scorched needles are shed.

We did not measure soil nitrogen levels, but foliar nitrogen averaged 8.5 g kg^{-1} across all treatments and there were no differences among any of the treatments at an alpha level of 0.15. We applied less nitrogen than others recommended for managing pine stands for straw production." In the past, however, maturing slash pine (P. *elliottii* Engelm. var. *elliottii)* stands in the West Gulf Coastal Plain have failed to respond to nitrogen fertilization.[27]

3.5. *Longleaf pine growth and yield*

Silvicultural practices can have dynamic effects on forest stand development, which can vary from year to year for several growing seasons.[28] Over 3 years in this study, straw harvesting adversely affected longleaf pine dbh and inside bark volume $m^3 ha^{-1}$ productivity when comparing the burned-only and burned and two harvest treatments (a = 0.0789 and 0.1375, respectively) (Table 2). The application of DAP fertilizer increased pine basal area slightly ($\alpha = 0.1475$).[23]

After 4 years of management, fertilization and straw harvesting practices were having interactive effects on longleaf pine growth in these now 38-year-old stands. Treatments 3 and 4 reduced longleaf pine growth by 0.3 cm dbh, 0.56 m^2 basal area ha^{-1}, and 5.34 m^3 i.b. ha^{-1} when compared with the unharvested treatments 1 and 2. Broadcasting 280 kg ha^{-1} DAP coupled with harvesting increased longleaf pine growth by 0.05 cm dbh, 0.17 m^2 basal area ha-‘, and 1.98 m^3 i.b. ha^{-1} when compared with the fertilized-unharvested subplots.

However, these 4 year treatment effects were temporary. After 5 years, the February 1996 results found no statistically significant differences between fertilization levels or among the four subplot treatments for pine dbh, total height, and volume per hectare (Table 2).

There was an interaction between fertilization and management practices for basal area per hectare at $\alpha = 0.1254$. The basal area least squares mean value was greatest on the unfertilized control subplot but least on the fertilized control subplots. Conversely, the basal area least squares mean value was least on the unfertilized annually harvested subplots but greatest on the fertilized annually harvested subplots after five growing seasons (Table 2).

The annual harvesting practices may have adversely affected tree development but would also provide weed control (Table 6). Combining the use of fertilizer with weed control is known to increase pine productivity.[29] Apparently, the combination of fertilization and weed control resulting from the harvesting of straw had some beneficial effect on stand basal area, but this effect was not sufficiently strong to be demonstrated in the other measured tree variables. The apparent change in stand responses to treatments from year-to-year was partly due to the low power inherent in this experiment and the generally slow periodic growth rate of the longleaf pine on this site.

3.6. *Herbaceous plant community effects*

Fertilization significantly increased total current-year herbaceous plant production (oven-dried basis) by an average of 58% when compared with the unfertilized treatment (Table 5). On average the managed subplots produced significantly more herbaceous plant biomass than the control treatments. However, this difference was greatest between the control and burned and two harvests treatments. The burned and two harvests treatment produced significantly more total herbaceous plant production than either the burned-only or annually harvested treatments.

Therefore, two harvests followed by several years of rest had the greatest positive effect on total current-year herbaceous plant productivity (Table 5). This is not surprising because the activities associated with straw harvesting cleaned underbrush from the subplots, and the cessation of harvesting for several years allowed the herbaceous community to redevelop. Continuation of burning on these subplots should help keep the underbrush in check. The problem with annual straw harvesting is that it keeps the herbaceous plant community from fully redeveloping, and the control treatment does nothing to check underbrush growth.

However, plant community development can not be judged solely on total biomass production. Certain plant groups are more desirable than others. Therefore, how were the individual plant taxa influenced by the different management schemes?

Table 5. Current-year herbaceous plant productivity (oven-dried basis) in July 1997

Main and subplot treatments	Pinehill bluestem	Slender bluestem	Other bluestems	Other grasses	Grass-likes	Forbs	Ferns	Total biomass
No fertilizer								
Control	90	[a]	–	38	12	82	230	452
Burned-only	327	14	17	140	23	225	34	780
Burned and two straw harvests	188		5	425	9	380	81	1088
Annually harvested	31	43	22	291	7	126		519
	159	14	11	223	13	203	86	710
50 kg ha^{-1} N and 56 kg ha-'								
Control	54	2		13	–	51	351	472
Burned-only	296	27	47	108	13	394	335	1220
Burned and two straw harvests	188	7	87	279	16	521	696	1795
Annually harvested	293	–	76	367	31	239	10	1015
	208	9	53	192	15	301	348	1125
								(Probability > F-value)
Analysis of variance								
Block								0.0777
Fertilizer								0.0282
Main error mean square								86777.60
Subplot treatments								0.0001
Control vs. stand management								0.0002
Burned-only vs. burned and two straw harvests								0.0006
Burned-only and two straw harvests vs. six annual harvests								0.0143
Fertilizer by subplot interaction								0.2318
Subplot error mean square								105820.18

Sub-divided into seven taxa—pinehill bluestem, slender bluestem, other bluestem, other grasses, forbs, and ferns.
[a]Taxon was not present in the-sample

On the unfertilized triennially burned treatment, pinehill bluestem continued to be the most common taxon of the seven taxa subdivisions (Table 5). Pinehill bluestem averaged 42% of the total herbaceous plant biomass. Burning is a standard method for managing understorey vegetation in longleaf pine forests, and pinehill bluestem is often the dominant herbaceous plant on upland longleaf landscapes on the West Gulf Coastal Plain."

When fertilizers were applied to triennially burned plots, the forb taxon was the most productive and averaged 32% of the total herbaceous plant biomass. The most common forbs were bushy aster (Aster *dumosus* L.), fireweed *(Erechtites hieracifolia* (L.) Raf.), swamp sunflower *(Helianthus angustifolius* L.), poor-Joe *(Diodia teres* Walt.), showy partridgepea (*Cassia fasiculata* Michx.), pencilflower *(Stylosanthes biflora* (L.) BSP.), and weak tephrosia *(Tephrosia onobrychoides* Nutt.). The frequency of occurrence of these forbs ranged from 25 to 58%. Two other taxa, pinehill blue stem and ferns comprised 24 and 27% of the biomass, respectively. The use of fertilizers had therefore clearly influenced which plants dominate in the herbaceous plant community on longleaf pine uplands that were managed with fire.

On both the fertilized and unfertilized control treatments, ferns were the most common plant taxon 7 years after all management ceased (Table 5). The ferns averaged 63% of the total current-year herbaceous plant biomass on the controls. Bracken fern *(Pteridium aquilinum* var. *pseudocaudatum* (Clute) Heller) was the most common fern but Japanese climbing fern *(Lygodium japanicum* Thunb.), an escaped ornamental in the southern U.S.A., was also present.

On both the fertilized and unfertilized annually harvested treatments, other grasses, principally the low panicums, were the most common taxon (Table 5). The other grasses averaged 43% of the total herbaceous plant biomass.

On the unfertilized-burned and two harvests treatment, the other grasses were also the dominant taxon and comprised 39% of the total herbaceous plant biomass (Table 5). However, the most frequently occurring grasses were the low panicums, tall panicums, and pinehill bluestem. This suggested that when fertilizer was not used, the vegetation would begin to shift back to the originally dominant grass, pinehill bluestem, when straw harvesting had ceased. If fertilizers were used and straw harvesting had stopped, the ferns became the dominant taxon, comprising 39% of the total herbaceous plant biomass. Bracken fern was the most common. The other important taxon on the fertilized subplots was the forbs, which comprised 29% of the total biomass.

4. CONCLUSIONS

Crown scorch caused the premature senescence of some needles, but the monthly trends in needle fall and the total annual amounts of needle fall were unaffected by management practices. Harvesting the fallen pine straw was observed to have removed most of the forest floor and exposed the mineral soil. This was associated with increased soil bulk density. However, the cessation of harvest was followed by a modest recovery in soil bulk density over a 4-year period. Soils can thus recover following a limited number of straw harvests.

Broadcasting 280 kg ha^{-1} of DAP fertilizer increased phosphorus concentrations in the soil and living longleaf pine needles, but did not influence the productivity of the pine trees over a 5-year period.

Treatments which may have little significant influence on overstorey pine tree growth and yield can radically affect the understorey plant community. If maintenance of the herbaceous plant community is most important, then burning should be continual and pine straw harvesting should not be practised. If annual income from straw harvesting is desired, then pine straw management can be practised with little concern for loss in stand volume production.

Current best management recommendations for harvesting pine straw include periodic fertilizations with 150-200 kg ha^{-1} N and 56 kg ha^{-1} P and the mineral soil should not be exposed." Straw should not be harvested on soils with more than 10% slopes or on streamslide areas. Our results suggest that these management actions will do no harm. Pine straw harvesting lessens fire hazard, provides annual revenue, and can increase total farm income.[30] Part of this additional income should be used to prevent or correct any site damage.

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